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Development of CCD cameras for soft X-ray imaging at the National Ignition Facility

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ABSTRACT

The Static X-Ray Imager (SXI) is a National Ignition Facility (NIF) diagnostic that uses a CCD camera to record time-integrated X-ray images of target features such as the laser entrance hole of hohlraums. SXI has two dedicated positioners on the NIF target chamber for viewing the target from above and below, and the X-ray energies of interest are 870 eV for the "soft" channel and 3 – 5 keV for the "hard" channels. The original cameras utilize a large format back-illuminated 2048 x 2048 CCD sensor with 24 micron pixels. Since the original sensor is no longer available, an effort was recently undertaken to build replacement cameras with suitable new sensors. Three of the new cameras use a commercially available front-illuminated CCD of similar size to the original, which has adequate sensitivity for the hard X-ray channels but not for the soft. For sensitivity below 1 keV, Lawrence Livermore National Laboratory (LLNL) had additional CCDs back-thinned and converted to back-illumination for use in the other two new cameras. In this paper we describe the characteristics of the new cameras and present performance data (quantum efficiency, flat field, and dynamic range) for the front- and back-illuminated cameras, with comparisons to the original cameras.

Keywords: National Ignition Facility, NIF, X-ray diagnostic, X-ray imaging, CCD, SXI, Quantum Efficiency, Front-illuminated CCD, Back-illuminated CCD

1. INTRODUCTION

The Static X-Ray Imager (SXI) is a National Ignition Facility (NIF) diagnostic used to record time-integrated X-ray images. While its primary use is to measure changes in the size of the hohlraum's laser entrance holes (LEH) [1], it has also been used as a diagnostic in laser pointing shots and other experiments. The SXI works on the same principal as the classic pinhole camera except that it records X-ray photons instead of visible light. Currently three X-ray charge-coupled device (CCD) cameras (two primary and one spare) are used. It has long been desired to have replacement cameras available in case of damage to the three, but the back-illuminated CCDs used are no longer available. LLNL worked with Spectral Instruments of Tucson, Arizona – the builder of the original three cameras – to find a suitable replacement CCD sensor and build a camera around it that could be used in SXI.

1.1 Current SXI

The SXI operates in two dedicated diagnostic positioners on the NIF target chamber. SXI-Upper is located on a port 18° from the target chamber north pole, and SXI-Lower is located on a port 19° from the south pole. The pinhole array at the tip of an SXI snout can be placed as close as 500 mm from target chamber center (TCC) without interfering with the NIF laser beams or other diagnostics, although typically the standoff is 1.63 m for the nominal magnification of 2x. The camera is placed at a fixed distance from the pinholes (nominally 4.88 m from TCC) at the back end of the second or inner stage that extends into the target chamber (Figure 1). To avoid damage, CCD cameras are used for shots with an expected neutron yield less than 5E+13 (< 1.7E+7 n/cm^2 fluence at 4.88 m) and are replaced with image plate for shots with higher neutron yield.

X-ray production can vary by orders of magnitude from shot to shot on NIF, so the dynamic range of SXI is extended by placing a range of filters over multiple pinholes at the tip of the snout. The filtering on different pinholes may also be designed for different types of experiments, thus providing flexibility and requiring fewer snout exchanges to support multiple types of shots. Figure 2 shows an SXI-Lower false-color image from a recent shot. The 25 μm pinholes were filtered with 10, 25, 50, and 60 μm of Ti plus 75 μm of Be. The pinhole with 50 μm of Ti provided the optimum image for this shot. The lightly-filtered pinholes with 10 and 25 μm of Ti produced saturated images with significant

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“blooming.” When the X-ray-generated electrons greatly exceeded the pixel full well capacity, the excess electrons spilled over to pixels up and down the same row in the image. In contrast, the image from the pinhole with the heaviest filtering appears dim.

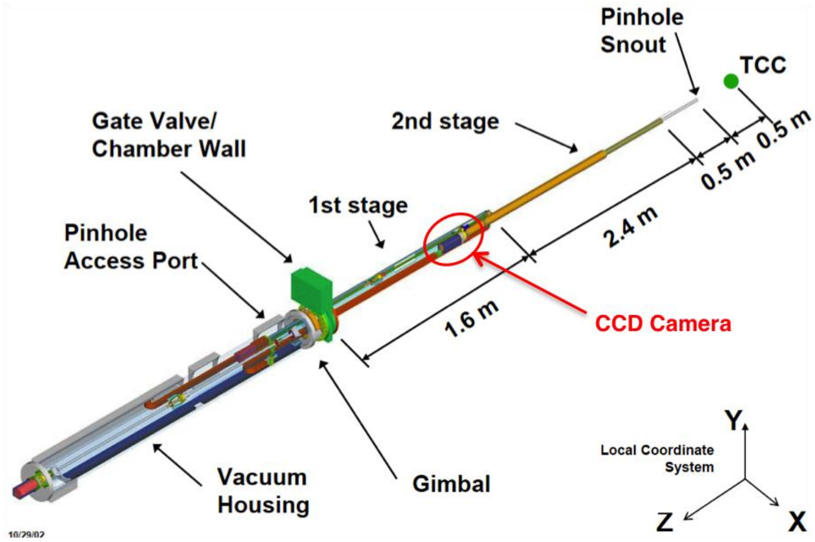

Figure 1. Drawing of an SXI positioner showing the location of the pinholes at the tip of the pinhole snout and the CCD camera at the back end of the second stage of the telescoping positioner.

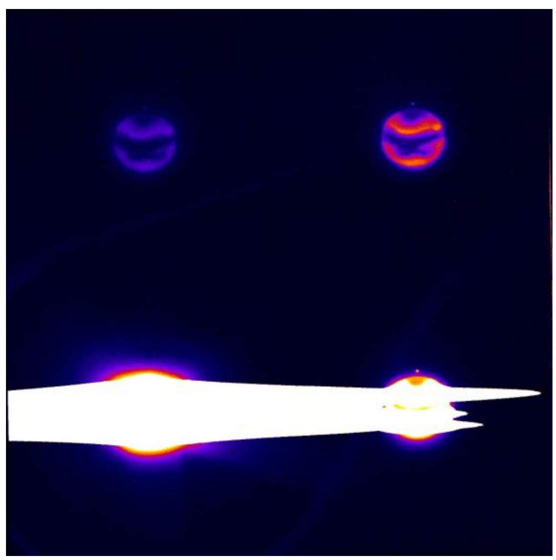

Figure 2. An SXI-Lower image (from shot N130405, C_Hohl_Sym_Warm_S05a) with a range of filtering across the pinholes. In addition to the 75 μm Be cover on the CCD camera, the two lower pinhole images were lightly filtered with 10 and 25 μm of Ti. These images saturated and bloomed heavily in the parallel readout direction. The upper left pinhole image had heavier filtering (60 μm Ti) and was dim. The upper right pinhole with 50 μm Ti filtering provided the best image for this shot.

By design, the filtering on SXI is nominally configured so that the energy sensitivity of the straight-through pinhole images (the “hard” channels) is 3 – 5 keV, but the back-illuminated CCDs have reasonable efficiency from ~700 eV to ~20 keV. There was a need to look at low energy X-rays at the peak of the thermal emission from the hohlraum in order to measure the fraction of the X-ray flux inside the LEH to correct the radiative drive measurements of the Dante diagnostic [1]. SXI-Upper was modified by installing a 10° angle-of-incidence multilayer X-ray mirror in the positioner just ahead of the CCD camera (Figure 3). The multilayer tungsten/boron carbide mirror was designed to reflect X-rays in a 100 eV band around 870 eV (the "soft" or mirror channel). Typically, a three-pinhole array is used with the mirror. Figure 4 shows an SXI-Upper image from the same recent shot as Figure 2. The two upper bright spots are straight-through images from 25 μm pinholes filtered by 20 or 50 μm of Ti with an additional 2 μm Cu and 1 μm polyimide from a light blocking filter in front of the CCD. The X-ray flux reflected from the mirror is faint (narrow band, ~0.18 reflectivity at peak) compared to the straight-through channels, so the mirror channel has a larger (typically 45 μm) pinhole and no additional filtering beyond the Cu/polyimide filter. The mirror channel image is seen at the bottom of the figure, while the shadow of the mirror can be seen at the top of the figure, outlined by the faint image of X-rays from the unconverted light shield around the hohlraum.

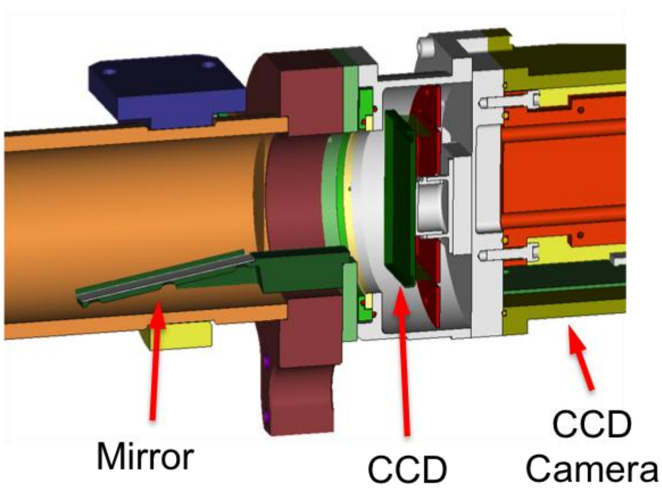

Figure 3. The 10° angle-of-incidence mirror placed ahead of the camera to reflect soft X-rays onto the CCD.

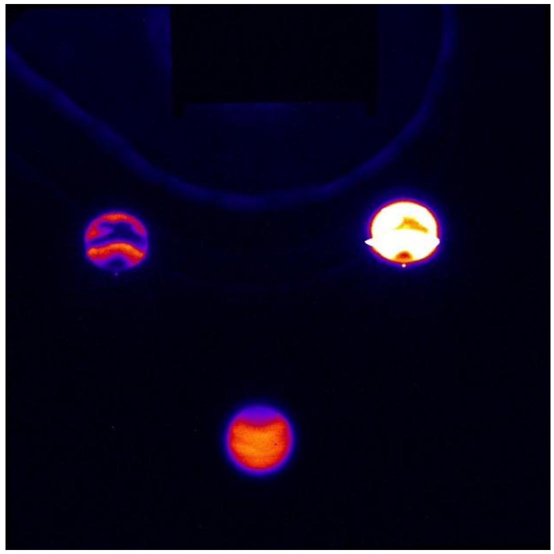

Figure 4. An SXI-Upper image showing two straight-through "hard" X-ray images (center) and one "soft" X-ray image reflected from the multilayer mirror (bottom). Note that the mirror image is upside-down compared to the straight-through images. The shadow of the mirror can be seen faintly (top center).

1.2 Description of the SXI CCD Camera

The three current SXI CCD cameras are modified Spectral Instruments SI-800 cameras adapted to a vacuum-immersible airbox enclosure that LLNL designed to operate in the NIF target chamber (Figure 5). Utilities available in the SXI positioners are 28 VDC power and chilled water for cooling the thermo-electric cooler (TEC) backplate. DC-DC voltage converters within the airbox provide the voltages needed by the camera electronics. The camera is controlled and data is downloaded via a fiber optic link to a computer running custom NIF software. A coaxial cable provides the NIF timing system trigger through a BNC connector.

The current cameras use a 2048 x 2048 CCD array of 24 x 24 μm pixels. This CCD measures 49 x 49 mm — large enough to capture multiple, non-overlapping images while allowing for the tolerances of the positioner pointing accuracy at magnifications up to 4x. Measurements at National Security Technologies, LLC (NSTec) have shown these back-illuminated CCDs have quantum efficiency (QE) greater than 0.3 between photon energies of 700 and 6500 eV, with one camera having a peak QE of 0.92 at 2345 eV. Back-illumination allows better quantum efficiency at X-ray energies below 3 keV than is possible in a front-illuminated CCD, as the latter's insulator layer and gate structure blocks some of the incident low energy X-rays and the QE suffers. Unfortunately the manufacturer of this CCD, Scientific Imaging Technologies, Inc. (SITe) went out of business many years ago, and these CCDs are no longer available. In order to be a drop-in replacement for the current camera, a large imaging sensor with similar dimensions was needed.

One issue with the current cameras is the number of hot pixels and column defects. The CCDs were not the highest grade when purchased so came with some defects and have seen some neutron damage from NIF yield shots. In order to limit further accumulated damage, a conservative practice was implemented to remove the cameras from the positioner and replace them with image plates when the expected neutron yield exceeds 5E+13. However, image plates must be removed and replaced after every shot so their use takes up some of the limited time that target bay personnel have to prepare for the next shot. The availability of replacement cameras would make it possible to be less conservative and use CCD cameras at higher yields with all the operational advantages of electronic readout.

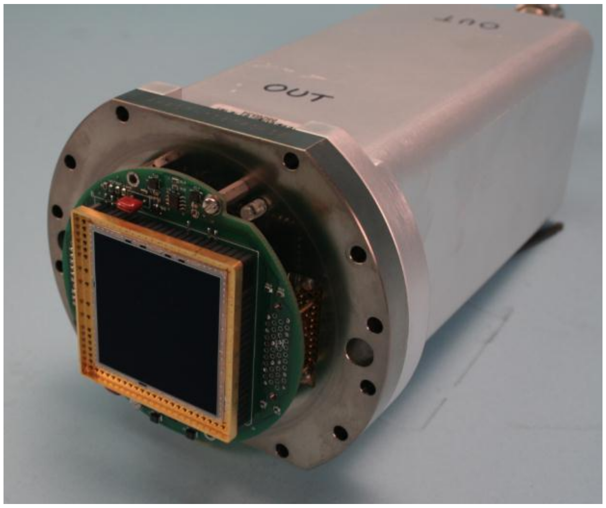

Figure 5. An SXI camera showing the exposed CCD. The camera electronics are contained within the vacuum-tight aluminum airbox housing. The cable connections are at the back of the camera (not visible in this photo).

2. PROCUREMENT OF REPLACEMENT SXI CAMERAS

2.1 Replacement CCD

The main barrier to the procurement of replacement SXI cameras was the availability of suitable image sensors. The required size, almost 2 inches square, is larger than necessary for most commercial applications so very few sensors of that size come on the market. As a maker of scientific CMOS and CCD cameras, Spectral Instruments regularly surveys the availability of commercial imaging sensors. They identified a family of CCDs manufactured by Teledyne Dalsa that uses 24 μm pixels, the same size as in the SITe CCD. The IA-DJ High Quanta is a family of front-illuminated full-frame CCDs intended for scientific and X-ray applications with three available sizes — 524 x 524, 1044 x 1044, and 2084 x 2084 pixels. The largest CCD has approximately the same area as the SITe CCD so it was identified as a candidate for use in a new camera. A comparison of specifications is shown in Table 1.

Table 1. Comparison of SITe and Dalsa CCD specifications [2],[3].

	SITe SI424A	**Teledyne Dalsa IA-DJ-02084**
Format	2048 x 2048 pixels	2084 x 2084 pixels
Pixel Size	24 μm x 24 μm	24 μm x 24 μm
Sensor Size	49 mm x 49 mm	50.02 mm x 50.02 mm
Illumination	Back	Front
Phases	3	2
Full Well	200,000 e^- (Typical)	170,000 e^- ((Typical)
Dynamic Range	28-40,000: 1 (Typical)	13,000:1 (Typical)
Output Structure	Source follower	Two-stage source follower

2.2 Test Camera Evaluation

In order to test the X-ray quantum efficiency (QE) of the CCD pixel design, Spectral Instruments (SI) acquired a 1044 x 1044 version of the sensor and built a test camera. The camera was sent to NSTec for characterization on their Manson medium resolution X-ray source [4]. NSTec is another U.S. Department of Energy/National Nuclear Security Administration contractor and is tasked with many of the calibrations of NIF target diagnostics. The Manson X-ray source uses a selection of anode and filter combinations and is capable of producing X-rays with energies from 710 eV (Fe anode with 1 μm Fe filter) to 8470 eV (Cu anode with 25 μm Mo filter). The quantum efficiency — the percentage of photons hitting a pixel that produce a signal — was measured and compared to two of the existing cameras (SXI-1 and SXI-3). Of the three existing cameras, SXI-1 has the best QE performance and SXI-3 has the lowest. As shown in Figure 6, the QE of the test camera was lower than the other cameras. In the range of 2 to 5 keV the test camera's QE was a half to a third of that of the other cameras. Below 1.5 keV the fall-off was even more dramatic. This can be attributed to the CCD's insulator layer and gate structure blocking some of the low energy X-ray photons.

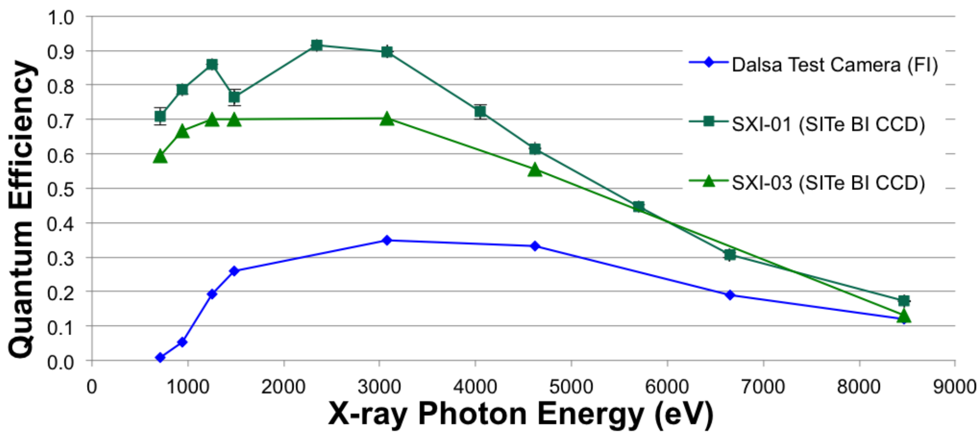

Figure 6. QE measured at various X-ray energies for the Dalsa Test Camera with front-illuminated CCD compared to two of the existing SXI cameras with back-illuminated CCDs

As discussed above, the SXI uses multiple pinholes with different amounts of filtering to increase the dynamic range of the measurement. It is possible to change the filtering to accommodate a lower QE at X-ray energies above 2 keV (e.g., for the hard channels), thus the front-illuminated sensor could be used in SXI-Lower. Unfortunately the poor performance below 1.5 keV makes a front-illuminated CCD unsuitable for SXI-Upper. At the 870 eV energy of the soft channel, the test camera QE of around 0.05 is an order of magnitude lower than the back-illuminated cameras. This difference cannot be accommodated for the faint soft channel image, which already uses minimal filtering.

2.3 Ordering New Cameras

Based on the results with the test camera it was decided to procure some of the new SXI cameras using the front-illuminated 2084 x 2084 CCD. The front-illuminated cameras for SXI-Lower would free up the existing cameras for use in SXI-Upper. However it was still important to procure new back-illuminated cameras, as well. SI inquired if Teledyne Dalsa would be willing to produce a back-illuminated version of the CCD, but they said there were no plans to release such a device. Fortunately, SI has a working relationship with the Imaging Technology Laboratory (ITL) at the University of Arizona, Tucson, which has the facilities to develop the back-thinning processes to convert imaging sensors, and ITL was willing to process devices in small lots on a "best effort" basis.

Two orders were placed with SI. The first was to produce a total of five new SXI CCD cameras, and the second was to have CCDs back-thinned, i.e., converted to back-illuminated sensors. For the first contract, three of the cameras (eventually designated SXI-5, SXI-7 and SXI-8) were outfitted with front-illuminated 2084 x 2084 pixel CCDs, while the other two were to be outfitted with back-illuminated CCDs from the second contract. To avoid a costly redesign of the SXI positioner, cables, or control software, the new cameras had to be drop-in replacements for the current cameras.

When the original cameras were built, LLNL provided the housing and power supplies, as they had to fit within the design of the overall diagnostic. For these new cameras, LLNL provided these designs to SI so they could be replicated. There were several mechanical design improvements, but the physical envelope of the new cameras is the same as the old, and they use the existing utilities and cables (power, cooling water, etc.) in the SXI positioners.

The second contract was for the conversion of CCDs to back illumination. For this, SI purchased nine CCDs still on the wafer directly from Teledyne Dalsa. These were transferred to the ITL facility in Tucson where the wafers were diced. The sensor dies were then back-thinned (Si substrate etched away up to the active layer of epitaxial Si) and coated with a thin passivation layer optimized for soft X-rays. The back-thinned sensors were packaged for testing and use. The processing at ITL yielded three usable back-thinned CCDs, two of which were installed in cameras (designated SXI-4 and SXI-6).

3. CALIBRATION RESULTS FOR A FRONT-ILLUMINATED CCD CAMERA

The three front-illuminated cameras were built with stock Teledyne Dalsa IA-DJ-02084 CCDs. One of these cameras (SXI-5) has gone through a set of X-ray camera calibrations at NSTec, which includes measurements of QE and camera efficiency, flat field response, linearity and dynamic range.

3.1 Quantum Efficiency

QE measurements for SXI-5 using the Manson X-ray source ranged from 1254 to 8470 eV. In addition, measurements were made at 9886 and 15780 eV in the NSTec High Energy X-ray (HEX) laboratory [4]. NSTec worked with Jim Dunn of LLNL to fit the QE data to a model that Dunn and Steel [5] developed for CCD QE based on Si K-edge X-ray absorption fine structure. The results in Figure 7 show a good fit of the model to the measured values.

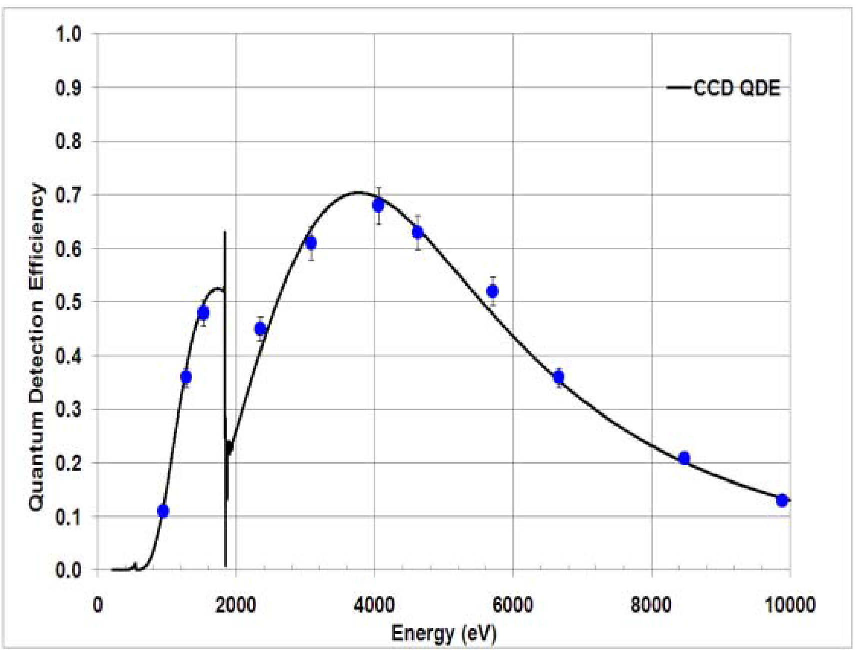

Figure 7. Comparison of SXI-05 QE data to a model as per Dunn and Steel [5]. The model used a 19 µm thick active detection region and a 3.0 µm electrode gate structure (0.7 µm Si, 1.9 µm SiO_2, 0.3 µm Si_3N_4). The material thicknesses from the manufacturer (Teledyne Dalsa) were not available. The point at 940 eV was taken from calibration measurements for SXI-8.

Figure 8 compares the QE curve of SXI-5 with two existing cameras (SXI-1 and SXI-3) and with the Dalsa Test Camera. Surprisingly SXI-5's QE was much higher than that of the Dalsa Test Camera. At 3 keV and above it was very close to the existing SXI cameras, which means that SXI-5 can be used in SXI-Lower with little or no change to the pinhole filtering. At 4620 eV and above, SXI-5 has higher QE than the existing cameras, indicating that the front-illuminated CCD has a thicker layer of photosensitive epitaxial Si than the back-illuminated sensors for which some of that layer is removed. At 2340 eV and below, the QE is lower than the existing cameras due to the filtering effect of the gate structure and SiO_2 insulator that the photons must travel through to reach the epitaxial Si.

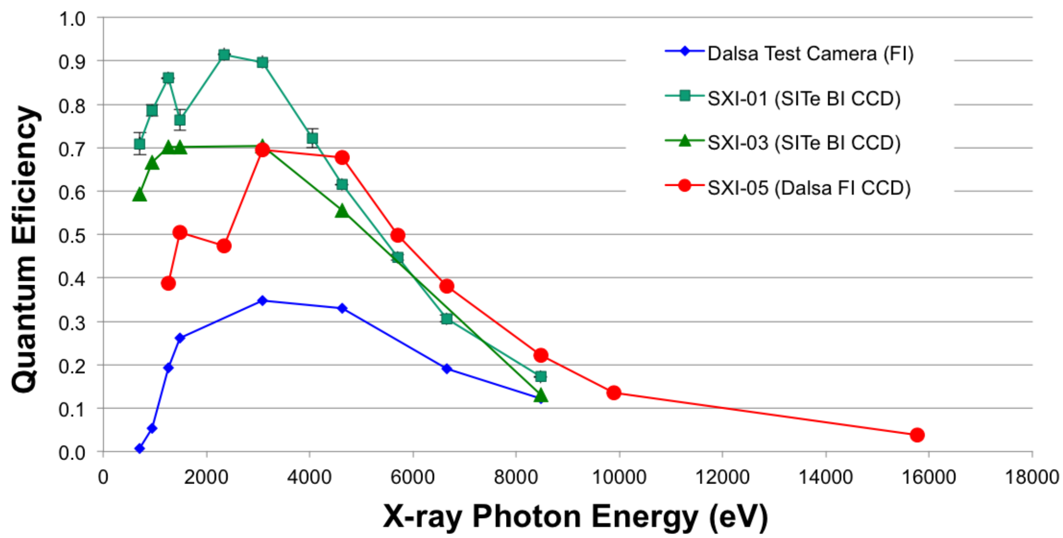

Figure 8. QE curve for camera SXI-5 with a front-illuminated CCD compared to the Dalsa Test Camera and two of the existing SXI cameras with back-illuminated CCDs.

3.2 Dynamic Range

The dynamic range of the camera was measured using a variance photon transfer method.[6] The curve deviates from linear at about 45,000 counts. The read noise in a bias image (no light exposure and no integration time) was about 10 counts, giving a dynamic range of approximately 4500:1.

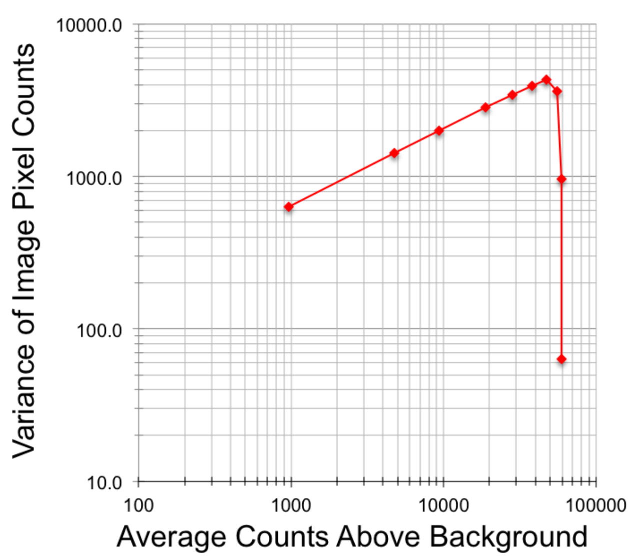

Figure 9. Variance photon transfer curve showing deviation from linear around 45,000 counts

3.3 Flat Field Response

The X-ray emission spot of the Manson source is approximately 1 mm in diameter. The large size of the SXI CCD and limiting apertures within the Manson source make it necessary to place the CCD approximately 1.5 m from the emission spot to provide very uniform illumination over the entire sensor for flat field measurements. Flat field measurements are used to generate correction masks that compensate for pixel nonuniformity [7]. The masks contain values with a mean of 1.0 such that the responsivity of each pixel is normalized to the same level when multiplied by the mask value.

Figure 10 contains a flat field mask for SXI-5 with 8470 eV illumination. Figure 11 displays horizontal and vertical lineouts at three locations across the mask. These results show that the responsivity is very uniform and varies by less than a few percent across the sensor.

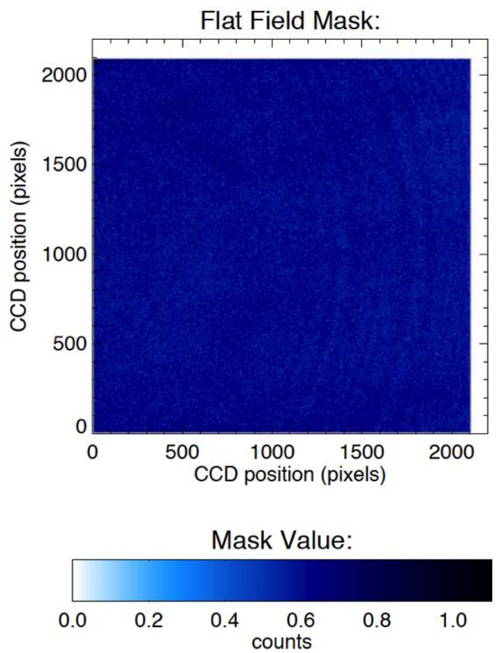

Figure 10. Multiplicative flat field mask for SXI-5 with 8470 eV X-ray illumination.

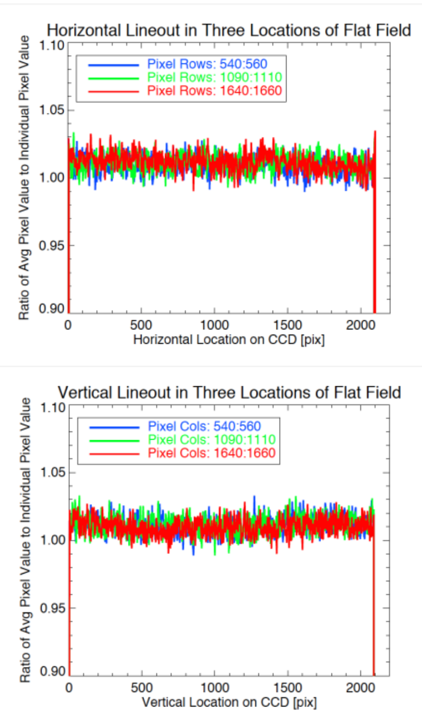

Figure 11. Lineouts of the average of 21 columns approximately ¼, ½, and ¾ of the way across the CCD in the horizontal and vertical directions.

4. CALIBRATION RESULTS FOR A BACK-ILLUMINATED CCD CAMERA

Two of the converted back-illuminated CCDs were installed in cameras SXI-4 and SXI-6. Preliminary measurements on SXI-4 indicate these cameras exhibit higher readout noise and more bad pixels (high dark current or low sensitivity) than the front-illuminated cameras. One possible source of noise is longer traces on the sensor package that were necessary because of the reversal of the bond pads to mount the CCD back-side up (flipped over relative to the front-illuminated CCDs). These long traces appear to be acting as antennas, picking up readout noise, power supply noise, and other electromagnetic interference. Also, though many pixels were evidently damaged during the back-thinning processes, the level of damage is less than or comparable to the original SXI cameras, and hence probably acceptable for use at NIF. The dynamic range of the back-illuminated cameras has yet to be fully quantified, but from early tests it appears that the upper limit of the linear response is 30–40% higher than that of the front-illuminated cameras.

4.1 Quantum Efficiency

Figure 12 compares the QE curve of SXI-4 with two existing cameras (SXI-1 and SXI-3) and with front-illuminated SXI-5. The QE is very close to that of SXI-1, the better of the two existing cameras. As expected, below 3 keV the QE is much better than SXI-5 due to the latter having gate structure and an insulator layer that the X-rays must penetrate. At the lowest energies, 710 and 940 eV, SXI-4 shows even higher QE than SXI-1, which is very desirable for use with the soft X-ray mirror channel on SXI-Upper.

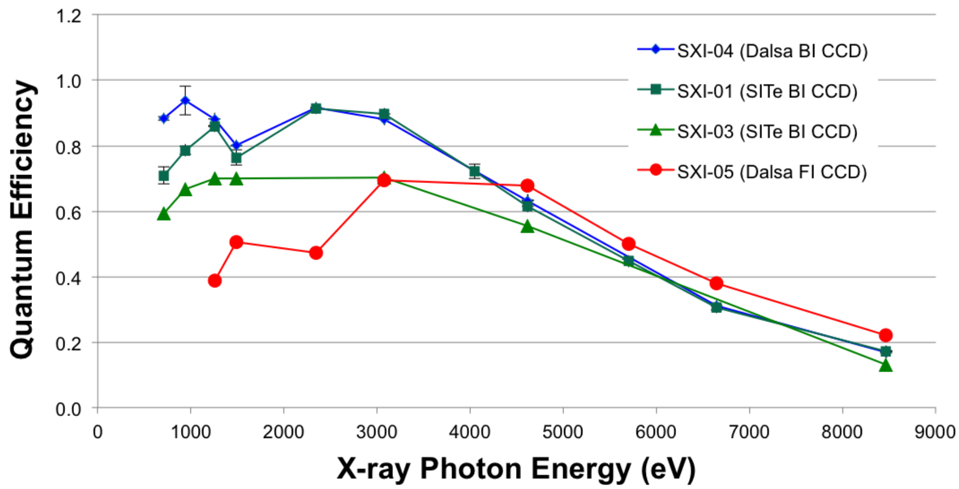

Figure 12. QE curve for camera SXI-4 with a back-illuminated CCD compared to SXI-5 with a front-illuminated CCD and two of the existing SXI cameras with back-illuminated CCDs.

4.2 Flat Field Response

Figure 13 contains a flat field mask for SXI-4 with 1254 eV illumination. The circular defect seen in the upper right corner is a less sensitive spot that was damaged during the back-thinning processes. Fortunately it is in the corner where it is unlikely to interfere with any data images. There are also several damaged columns that are also in a fortunate position along the edge of the sensor. At this soft X-ray energy there is some variation in responsivity that may be caused by nonuniformity in the passivation layer or any contamination on the surface. Figure 14 contains horizontal and vertical lineouts showing variation of only a few percent across the sensor.

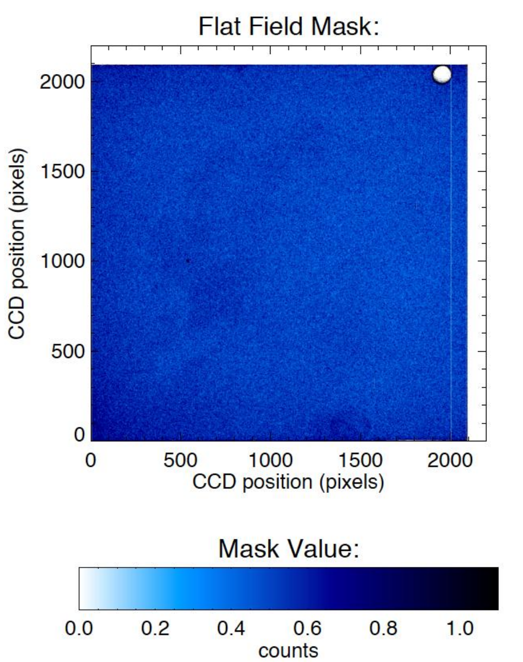

Figure 13. Multiplicative flat field mask for SXI-4 with 1254 eV X-ray illumination.

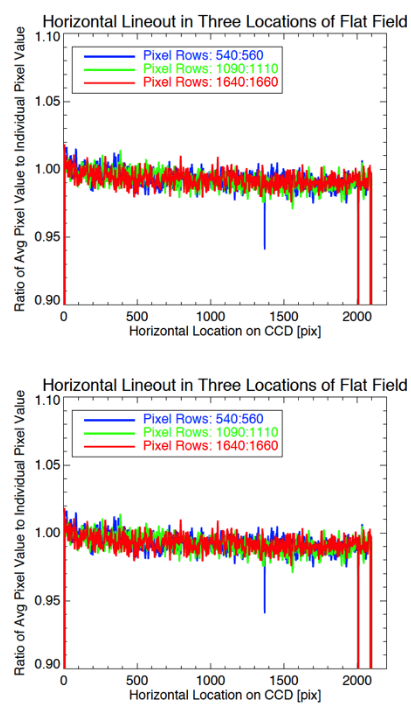

Figure 14. Lineouts of the average of 21 columns approximately ¼, ½, and ¾ of the way across the CCD in the horizontal and vertical directions.

Figure 15 contains the flat field mask for SXI-4 with 8470 eV illumination. At this energy, photons penetrate all the way through the photosensitive epitaxial layer of the back-thinned CCD. Thus any variation in thickness during the etching process can have a measurable effect on flat field response, since a thinner section will stop fewer photons [4]. From the flat field mask below it appears that the back-thinned CCD is thicker (more responsive) in the center and thinner near the edges. As shown in Figure 16, the variation in responsivity across the sensor is as much as 10%. Again, it is fortunate that the greatest variations are near the edges where they are less likely to affect data images.

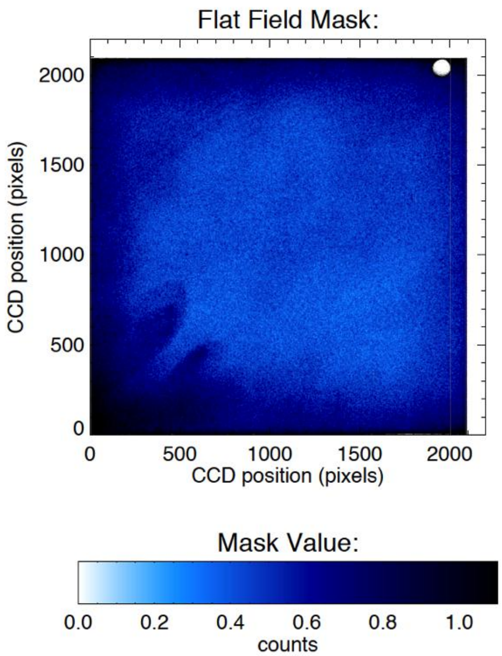

Figure 15. Multiplicative flat field mask for SXI-4 with 8470 eV X-ray illumination.

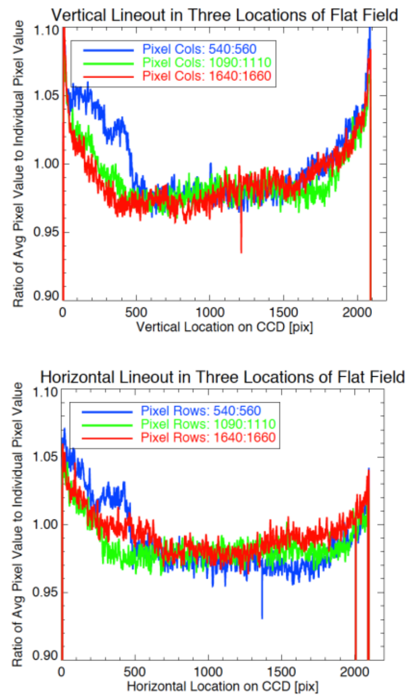

Figure 16. Lineouts of the average of 21 columns approximately ¼, ½, and ¾ of the way across the CCD in the horizontal and vertical directions.

5. CONCLUSION AND FUTURE WORK

The cameras with front-illuminated CCDs — SXI-5, SXI-7, and SXI-8 — have pristine sensors with very low noise, adequate dynamic range, and QE that is suitable for use in SXI-Lower (which has only hard X-ray channels). In comparison, the cameras with back-illuminated CCDs — SXI-4 and SXI-6 — have more damaged pixels and higher readout noise (comparable to the original SXI cameras), but have excellent QE at low energies and slightly higher dynamic range. The back-illuminated cameras will undergo further testing before it is decided how they will be used, but they appear to be suitable for SXI-Upper with its soft X-ray mirror channel.

The new cameras were designed to use the existing cables and utilities in the SXI positioners (28 VDC power, 62.5/125 μm multimode optical fibers, cooling water, and electrical trigger), but use a faster gigabit communication interface. Control computers with upgraded gigabit interface boards have been installed and tested at NIF. Cameras are undergoing testing to meet NIF cleanliness and low-outgassing standards, and calibrations will be completed at NSTec before the new cameras are installed and commissioned at NIF.

ACKNOWLEDGMENTS

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